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Objective Identification of Frontal Wave Cyclones

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Summary: This brief paper further develops the objective front-plotting methodology described in Hewson (1996), to allow the tips of frontal wave cyclones to also be objectively identified. The method embraces a new definition of frontal waves, but is analogous to operational practice in that these waves are located where cold and warm fronts join. It is suggested that for the early stages of cyclonic development the new methodology will perform better than those previously published.

1. Introduction

Extratropical cyclones can pose considerable problems for the forecaster. This applies across a wide range of scales, from relatively small, flat, non-developing frontal waves, through to large, explosively-deepening cyclones. The purpose of this brief paper is to demonstrate ways in which objective methods can help speed up and improve the analysis of such features, and hence improve the forecasts of weather associated with them.

The reader is referred to Kurz (1995) for an introductory discussion of frontal wave cyclones.

2. Objective fronts

A recent paper (Hewson, 1996) described a methodology by which mathematical and graphical techniques can be combined to enable a computer to draw fronts entirely automatically, using gridded numerical model data as an input. The set of defining equations, which is reproduced in full in the Appendix, may be summarised as:

(2nd spatial derivative, in the cross-front direction, of the magnitude of the thermal gradient) $= 0$ **[L1]**

(Cross-front rate of change of thermal gradient, in the direction of the cold air) $> K_1$ **[M1]**

(Thermal gradient in the adjacent baroclinic zone) $> K_2$ **[M2]**

The letter '**L**' denotes 'locating equation', whilst the letter '**M**' denotes 'masking inequality'. Thermal gradients are computed using a specific thermal parameter, such as potential temperature or wet-bulb potential temperature, whilst K_1 and K_2 represent threshold values. Figure 1 shows an example of objective fronts plotted using the equations. Thin dashed contours show the input wet-bulb potential

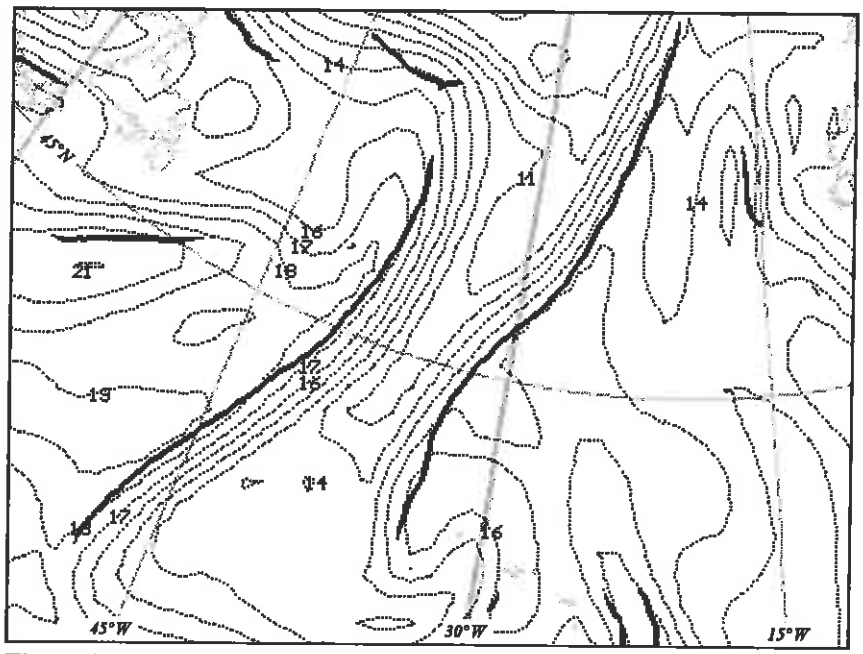

Figure 1: Example showing objective surface fronts (thick black lines) plotted on the 900 hPa wet-bulb potential temperature field from which they were derived (dashed contours, 1 deg C interval), over the North Atlantic. Data time is 0000UTC, 18th July 1996.

temperature field taken from the U.K.M.O. limited area model (LAM), whilst the thick solid lines are the objective fronts (on this figure no distinction is made between warm and cold fronts). The

fronts clearly lie along the warm air boundaries of the major baroclinic zones, in accordance with the definition of a front given in Hewson (1996), indicating that the recommended technique is accurate.

The data used to produce Figure 1 was taken from the 900hPa level; Hewson(1996) indicated that this was suitable for representing surface fronts.

3. Objective frontal waves

The defining equations for objective fronts can be extended to define the tips of objective frontal waves, at a particular atmospheric level. Two equations are required in addition to **[L1]**, **[M1]** and **[M2]**. These are:

(Geostrophic thermal advection) = 0 **[L2]**

(Angle α between vectors **A** and **B**) < 90° **[M3]**

where:

A is an along-front vector, with warm air to the right

B is the gradient of the geostrophic thermal advection

The Appendix gives full details. Equation **[L2]** simply defines a new set of contours which will intersect the contours defined by **[L1]** at points at which cold and warm fronts meet. These meeting points will consist of waves and 'anti-waves'. Inequality **[M3]** removes the 'anti-waves'. It is probably most helpful to think of waves as those meeting points where there is positive vorticity in the cross-front component of the geostrophic wind, and anti-waves as those points where this vorticity is negative. Note also that this paper restricts itself to locating the *tips* of frontal waves; no attempt is made to evaluate the horizontal extent, or wavelength, of a frontal wave (Nielsen & Dole, 1992, discuss this aspect).

On Figure 2 the red and blue lines are, respectively, objective warm and cold (surface) fronts. The thin arrows point to two locations at which warm and cold fronts meet, one of which is a (surface) wave and one a (surface) anti-wave. The highlighted wave is perhaps best described as a 'cold front wave' (see Figure 1 in Thorpe (1994)).

Black dots on Figure 2 show all the objectively-derived surface frontal wave tips from a 2-day sequence of LAM analyses; the green numbers show clock time in hours (UTC). The objective fronts and surface pressure contours (black) correspond to the start of the period. The basic plot was produced entirely automatically. It may be immediately apparent that the wave and the anti-wave that are labelled have been correctly distinguished by the objective procedure; however this fact can also be deduced by inferring cross-front geostrophic winds from the isobaric pattern, and then considering how these winds vary in the along-front direction.

Large arrows have been added to Figure 2 to highlight the tracks of three frontal waves (A, B and C) that were present at the start of the period. These can be clearly followed, for 45, 6 and 18 hours respectively. Other trackable features are also apparent. In some regions overplotting means that the behaviour of slow moving features is difficult to discern; there are several ways this problem could be overcome - by increasing the time interval, by zooming in on a particular region, or by animating. In regions of high topography, such as the French Alps and Greenland, numerous quasi-stationary waves have been recognised. Some of these are not genuine, but relate to the fact that the 900 hPa pressure surface utilised intersects topography, a problem that is discussed in Hewson (1996).

4. Cyclone life-cycles

The method for objectively plotting frontal waves is also appropriate for locating and tracking typical, developing, mid-latitude cyclones, many of which naturally start life as frontal waves. Most past studies which have investigated the origin and tracks of such cyclones (such as Nielsen & Dole (1992), Murray & Simmonds (1991) and Ayrault et al (1995)) locate these cyclones by using searching algorithms to find where there are mean sea level pressure minima, or low level vorticity maxima. Although these methods would perform better than the objective frontal wave methodology after a typical mid-latitude low has reached maturity, i.e. after it has lost a prominent frontal signature, they also have disadvantages. Firstly, the locations of any cyclone centres identified will not necessarily match up with the locations of any associated fronts. Secondly, the very early stages of development may be missed because a flat incipient wave, as drawn by a forecaster, will generally not be associated with a pressure minimum (denoted by a closed isobar), and may not be associated with a discrete vorticity maximum either (but rather an elongated vorticity strip). Figure 2 provides a good example of this; the letters plotted alongside the track of feature A show where in the wave's life cycle it was *first* possible to discern a cyclone on the basis of a local maximum in the LAM 900 hPa relative vorticity field (point labelled 'V'), or alternatively on the basis of the first closed isobar (label 'P'). Clearly the objective method allows this particular wave to be tracked much further back in time. The first time at which the chief U.K.M.O. forecaster analysed a frontal wave is also shown (labelled 'H'); this forecaster probably identified the wave on the basis of a number of factors, including guidance from satellite imagery. However the letter 'H' is also well after the first signature in the objective plot, suggesting that objective methods have potential to provide the forecaster with useful guidance, provided the model's analysis is believed.

Cyclone A on Figure 2 developed explosively west of the U.K. (38 hPa in 24 hrs), and as it did so parts of Scotland experienced severe gales, and received 2 inches of rain. The forecaster who has to produce warnings for such hazardous weather can only benefit from being able to recognise the cyclone very early in its life-cycle. The cyclone was in fact the subject of intensive observing period (IOP) 16 of the FASTEX international field experiment (see Joly et al (1997)), an experiment designed to investigate secondary cyclones throughout their life-cycles. Plots similar to Figure 2 were an important aid in planning flights during this and many other FASTEX IOPs.

5. Accuracy

Although the values of fundamental variables may be correct at every gridpoint, the accuracy with which a particular method can pinpoint a particular cyclonic feature using that data will still depend on the method itself.

The vorticity maximum and pressure minimum methods referred to in section 4 generally allow cyclones to only be located at particular gridpoints, which means the location accuracy will be limited to about $(1/\sqrt{2})\chi \approx 0.7\chi$, where χ is one gridlength. Greater accuracy can be achieved by using additional algorithms to give intermediate locations, as discussed by Murray and Simmonds (1991).

The objective frontal wave plotting methodology achieves quite high accuracy in positioning without the use of additional algorithms. This is because interpolation between gridpoints, via the graphical package contouring facility, is implicit in the technique. The accuracy obtained will generally be similar to the accuracy with which objective fronts are located, i.e. 0.1χ-0.5χ (see Hewson (1996)).

Equation (1) in the Appendix expresses the relationship between the accuracy of frontal wave position and the angle α. A value of α close to 90° signifies that the geostrophic thermal advection (equation **[L2]**) is close to zero along a finite length of an objective front (equation **[L1]**). In such situations we are at the limits of being able to identify a frontal wave at all, so it is not suprising that

the location accuracy decreases markedly (see examples given at end of Appendix). On these occasions a human forecaster or analyst would generally also have difficulty in recognising and locating any frontal waves. On Figure 2, near the letter 'A', the 'double wave' (overlapping dots) is a symptom of α approaching 90°. It seems likely that the utility of plots showing objective frontal waves (such as Figure 2) could be enhanced by colouring each wave according to its location error.

Note that the objective frontal wave tracks on Figure 2 *are* reasonably smooth. If the frontal wave tips had been constrained to coincide with gridpoints, as in the standard vorticity maximum and pressure minimum techniques, the tracks would have been less clear, and system velocities would have been more difficult to estimate.

One additonal factor that can contribute to irregularities in cyclone tracks in an 'analysis' sequence, such as that shown on Figure 2, is data assimilation.

6. Summary

Fronts and frontal wave cyclones relate directly to hazardous weather of many types, yet are extremely compact in that they can be represented, respectively, by just lines or points. Historically, these factors have made them extremely useful conceptual tools, particularly to the forecasting community. It seems that objective techniques for deriving the locations, such as those described in this paper, can only broaden their appeal.

Here we have defined tips of (objective) frontal waves to lie at all those meeting points of cold and warm (objective) fronts about which there is cyclonic rotation in the cross-front components of the geostrophic wind. This is a new definition, but one which accords with standard synoptic practice. The definition is encapsulated in a set of 2 equations, and 3 inequalities. Graphical processing of the these equations and inequalities allows objective frontal wave plots, such as Figure 2, to be automatically produced.

The main attraction of plots such as Figure 2 is that they can incorporate, on one page, and in an instructive, compact format, many of the salient features of an analysis or forecast sequence covering several times. Producing such a plot manually would clearly take a considerable time. Intercomparison of model forecasts, in terms of weather impact, would become much more straightforward if automated plots similar to this were available for each forecast run.

When considering the life-cycle of a typical mid-latitude cyclone, different locating methods will be suited to different phases. The new objective frontal wave methodology described here is well-suited to pinpointing a feature during the period from initiation through to maturity, whilst methods which utilise pressure minima or vorticity maxima are probably best suited to the mature and decaying phases.

Of course, not every cyclone fits the 'typical' category. Some frontal waves lead to significant weather, notably precipitation, even when they do not develop markedly. The new method is ideally suited to identifying such features. Conversely, cyclone development in areas of weak low level thermal gradient will be handled better by the other techniques.

The examples in this paper only relate to surface fronts and surface frontal waves. It would also be instructive to plot objective frontal waves at higher tropospheric levels, and to investigate the vertical coherence of frontal waves in general.

The handling of frontal wave cyclones by numerical models has often been criticised. Objective techniques now mean that model handling, in terms of location of development, frequency of development, mechanism for development, tracking and decay, can all, in principle, be rigorously tested.

Appendix

Equations **[L1]**, **[M1]** and **[M2]** below have been reproduced from Hewson (1996); they constitute a set of equations which together can define an objective front. τ is a surrogate for any thermodynamic variable, and ∇ is a 2-dimensional horizontal/pressure level gradient operator:

$$\partial(\nabla|\nabla\tau|)_s/\partial s = 0$$
$$\text{where unit axis } \hat{s} = \pm\nabla|\nabla\tau|/|\nabla|\nabla\tau||$$
[L1]

$$(-\nabla|\nabla\tau|\cdot(\nabla\tau/|\nabla\tau|)) > K_1$$
$$\text{where } K_{1(\min)} = 0$$
[M1]

$$|\nabla\tau|_{(\sim ABZ)} > K_2$$
$$\text{where } K_{2(\min)} = 0$$
$$\text{and } |\nabla\tau|_{(\sim ABZ)} = |\nabla\tau|_{(x,y)} + (m\chi)|\nabla|\nabla\tau||_{(x,y)}$$
[M2]

'~ABZ' denotes 'in the adjacent baroclinic zone', whilst $m\chi$ is a (positive) fraction (m) of a gridlength (χ) in the direction in which the local thermal gradient is increasing most rapidly.

A distinction can be drawn between warm and cold fronts by assessing the sign of the local geostrophic thermal advection (as recommended in Hewson (1996)). Thus warm fronts and cold fronts meet at points where the geostrophic thermal advection ($A_{G\tau}$) is zero, as given below (V_G is geostrophic wind velocity):

$$A_{G\tau} = -V_G\cdot\nabla\tau = 0$$
[L2]

The set of points which satisfy the four equations **[L1]**, **[L2]**, **[M1]** and **[M2]** is comprised solely of frontal waves and frontal 'anti-waves'. Frontal anti-waves can be detected by computing the angle α between two specific vectors, namely an *along-front vector* which has warm air to its right (**A**), and a vector which represents the gradient of geostrophic thermal advection (**B**). If at any point identified using **[L1]**, **[L2]**, **[M1]** and **[M2]** α is less than 90° then that point represents a true frontal wave, whilst if at any such point α is greater than 90° then that point is an 'anti-wave'. Finding whether α is less than 90° amounts to finding whether the dot product of the two vectors is positive. This dot product is written below; the left hand pair of large square brackets encloses vector **A**, and the right hand pair vector **B**. Vector **A** has been derived by computing the gradient of the diagnostic in the front locating equation **[L1]**, and rotating this clockwise by 90° by taking a cross product with the vertical unit vector $\hat{k}$.

$$\left[\nabla[\partial(\nabla|\nabla\tau|)_s/\partial s]\times\hat{k}\right]\cdot\left[\nabla[-V_G\cdot\nabla\tau]\right] > 0$$

As indicated by Hewson (1996) it is more convenient to approximate the cross-front vector by $\nabla|\nabla\tau|$, and thus the along-front vector by $\nabla|\nabla\tau| \times \hat{k}$. The previous equation then reduces to:

$$\left[\nabla|\nabla\tau| \times \hat{k}\right] \cdot \left[\nabla[-\mathbf{V_G}\cdot\nabla\tau]\right] > 0 \qquad \textbf{[M3]}$$

Thus five simultaneous equations - **[L1]**, **[L2]**, **[M1]**, **[M2]** and **[M3]** - can successfully identify points on a 2-dimensional pseudo-horizontal surface which are the tips of objective frontal waves.

If the error bars on the contours given by **[L1]** and **[L2]** are the same ($=\delta\epsilon$), and the contours are assumed to be straight, then the error domain for a particular objective frontal wave is a rhombus centred on the contours' intersection point. We define the frontal wave location error $\delta\epsilon_{wave}$ to be proportional to the long diagonal of this rhombus, scaled to equal $\delta\epsilon$ when the contours are perpendicular. Simple geometry then gives:

$$\delta\epsilon_{wave} = \frac{\delta\epsilon}{\sqrt{1 - \sin\alpha}} \qquad (1)$$

or alternatively:

$$\delta\epsilon_{wave} = \delta\epsilon \left[1 - \frac{\left|\nabla|\nabla\tau| \cdot \nabla[-\mathbf{V_G}\cdot\nabla\tau]\right|}{|\nabla|\nabla\tau||\,|\nabla[-\mathbf{V_G}\cdot\nabla\tau]|} \right]^{-\frac{1}{2}}$$

The following pairings (α, $\delta\epsilon_{wave}$) illustrate the error characteristics implied by equation (1) if $\delta\epsilon$ is set to 0.3:

(0, 0.3), (15°,0.3), (30°,0.4), (45°,0.6), (60°,0.8), (75°,1.6), (90°,∞).

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